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USACE Directory of Expertise for Risk & Reliability



USACE Asset Management

Workshop

An Overview of Engineering Risk and Reliability Methods for USACE Studies

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Overview of Engineering Risk & Reliability Outline of Presentation

1. What is Risk? What is Reliability? Why is it Used?
2. Engineering Reliability Modeling Characteristics
3. Acceptable Methods for Engineering Reliability
4. Basic Features of Reliability Modeling and Analysis
5. Consequence Event Trees
6. New Engineering Reliability Guidance
7. New USACE DX for Risk and Reliability



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Five Required Elements of Risk

1. Likelihood – future uncertainty of an event
2. Outcome – link paired with likelihood in risk profile
3. Significance – amount of gain/loss for a particular outcome
4. Casual Scenario – causes of an event & subsequent outcome
5. Population – important aspect for life safety issues



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Risk Assessment/Management

Risk Assessment Determines:

- ✓ Likelihood
- ✓ Outcome
- ✓ Causal Scenario
- ✓ Population

Risk Management Determines:

- ✓ Significance
- ✓ Course of Risk Aversion/Mitigation
- ✓ Risk vs. Cost Tradeoffs

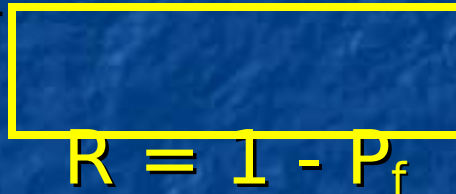


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Reliability Analysis

Reliability – probability that a system will perform its intended function for a specific period of time under a given set of conditions


$$R = 1 - P_f$$

Reliability is the probability that unsatisfactory performance or failure will not occur



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Reliability Analysis

Probability of Failure (P_f) – easily defined for recurring events and replicate components (such as light bulbs, etc...)

Probability of Unsatisfactory Performance (PUP)

- ✓ Tough to define for non-recurring events
- ✓ Typically, USACE structural elements fall into this category for a variety of reasons
- ✓ Examples (sliding of gravity structures, fatigue cracking of gates, etc...)
- ✓ Many times can be classified as an “economic failure” when consequences are significant



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Relationship Between Risk & Reliability

Costs * PUP = Consequences → Risk



**Annual probabilities computed from
an engineering reliability model**

Cost Examples for USACE Projects

Emergency Repairs

Delay Times for Users

Increased O & M Costs and/or Frequency

Damages to Users

Benefits Foregone

← Event Tree



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Reliability Modeling Basics

Probabilistic Modeling the Current and Future
Condition of Structures/Components for Decision
Making

Historical Information About Component

- Previous Maintenance and Failures
- Accounts for Historical Patterns and Future Condition

Realizes Probabilistic Nature of Engineering Analysis

Develop Probabilities of Unsatisfactory Performance
for Components Over Period of Study



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Reliability Analysis - Why is It Used?

Analysis Tool Used by USACE to Prioritize Investments

- Major Rehabilitation Studies
- Dam Safety Portfolio Risk Assessment

Recognizes and Captures Uncertainty in Analyses

- Engineering Uncertainties – Loads, Material Properties, Corrosion, Fatigue, Stress Concentration Factors, Etc...
- Economic Uncertainties – Traffic Forecasts, Rate Savings

Shows Economic Justification and Risks Associated with Multiple Future Investment Alternatives

- Fix-as-Fails Maintenance, Advance Maintenance, Major Rehab

Allows a Method to Rank Projects Based Upon Risks Associated with Life Safety and Economics



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Reliability Modeling Characteristics

Investment Tool for Decision Making

- Measures the risk (life safety/\$\$\$ damages) associated with performance of a component and/or system of components
- Reliability model itself is just one piece of the overall analysis. Integrates with consequence analysis through event trees.
- For an overall project, all critical components are analyzed to determine their performance through the study period (50 years for most USACE studies)



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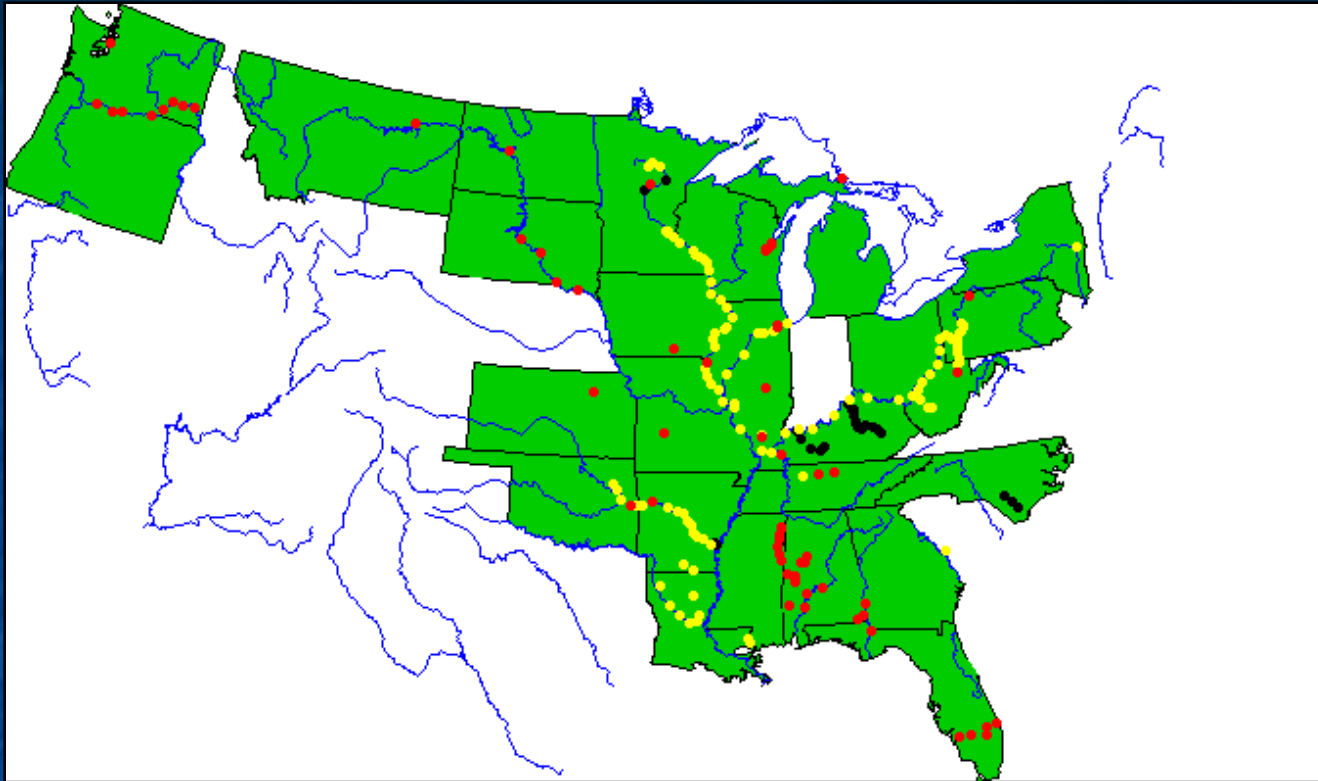


Aging Infrastructure **Prioritization**

Navigation Projects
Flood Control Projects

Where are our biggest risks to life safety?
What are greatest needs for navigation system?

USACE Navigation Projects – Aging Infrastructure



VITAL STATISTICS

238 lock chambers

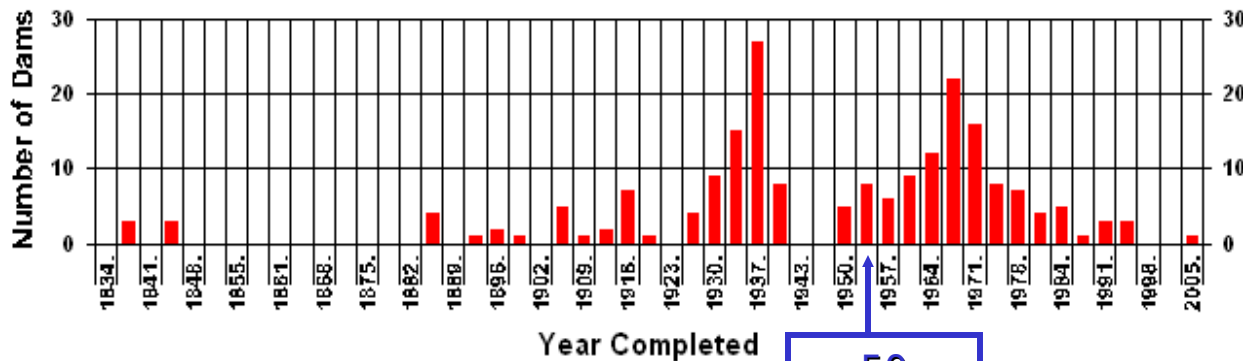
Average age = 58 years

Median age = 51 years

46% over 50 years

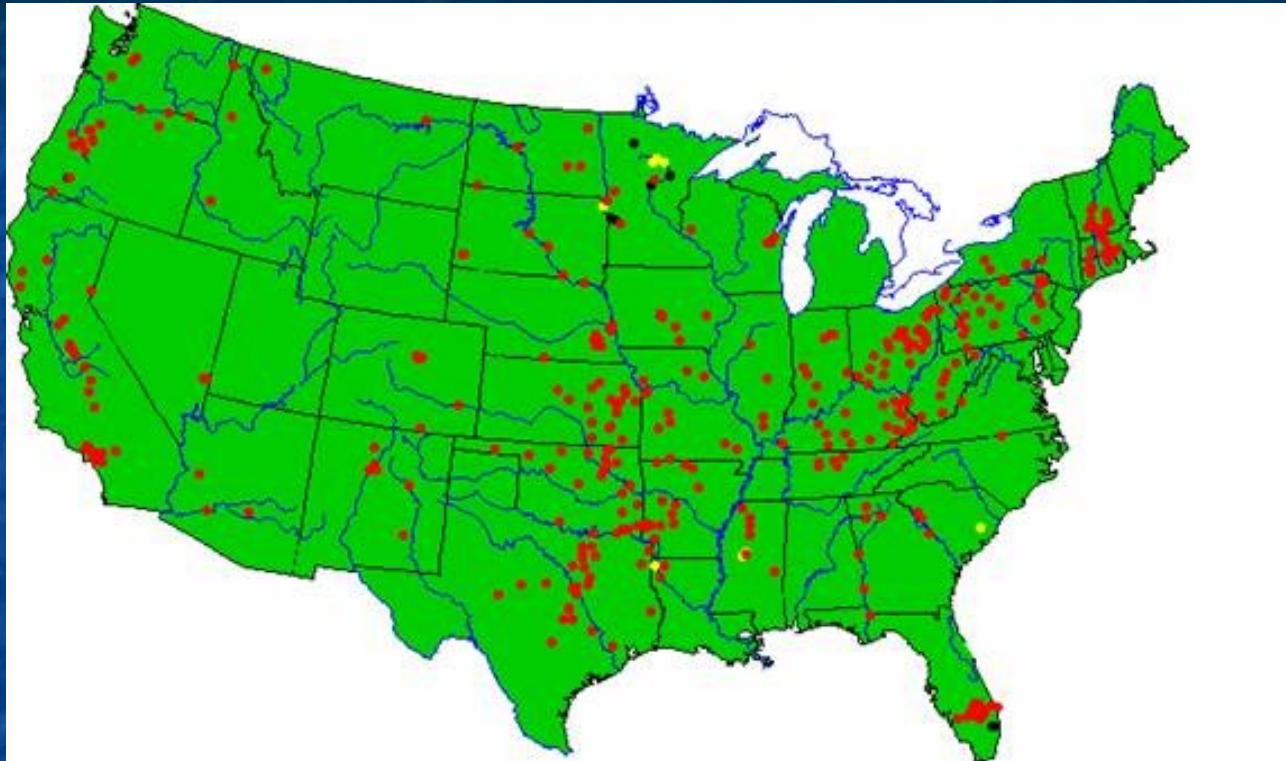
58% in next 10 years

- Low hazard project
- Significant hazard
- High hazard project



50
years

USACE Flood Control Projects – Aging Infrastructure



VITAL STATISTICS

400 flood control dams

Average age = 46 years

Median age = 44 years

42% over 50 years

67% in next 10 years

- Low hazard project
- Significant hazard
- High hazard project





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Acceptable Methods for Reliability Analysis

Engineering Reliability Analysis

Currently Four Acceptable Methods in Guidance

Reliability Index Method (Probabilistic Method)

Uses Beta values to determine point estimates of reliability

Not applicable for time dependent situations, issues w/ multiple random variables in the analysis

Originally used when software and computational packages were limited

Hazard Functions Analysis (Probabilistic Method)

Preferred method using analytical models with Monte Carlo simulation dependency and multiple, correlated random variables

Handles time

State-of-the-art method used on ORMSS, Markland Rehab Study

Historical Frequency of Occurrence / Survivorship Curves

Best method but database of failures not available for civil works structures

Applicable for other components, such as motors

Expert Elicitation Process

Uses judgment from a panel of experts to establish failure probabilities

Only used to supplement analytical methods

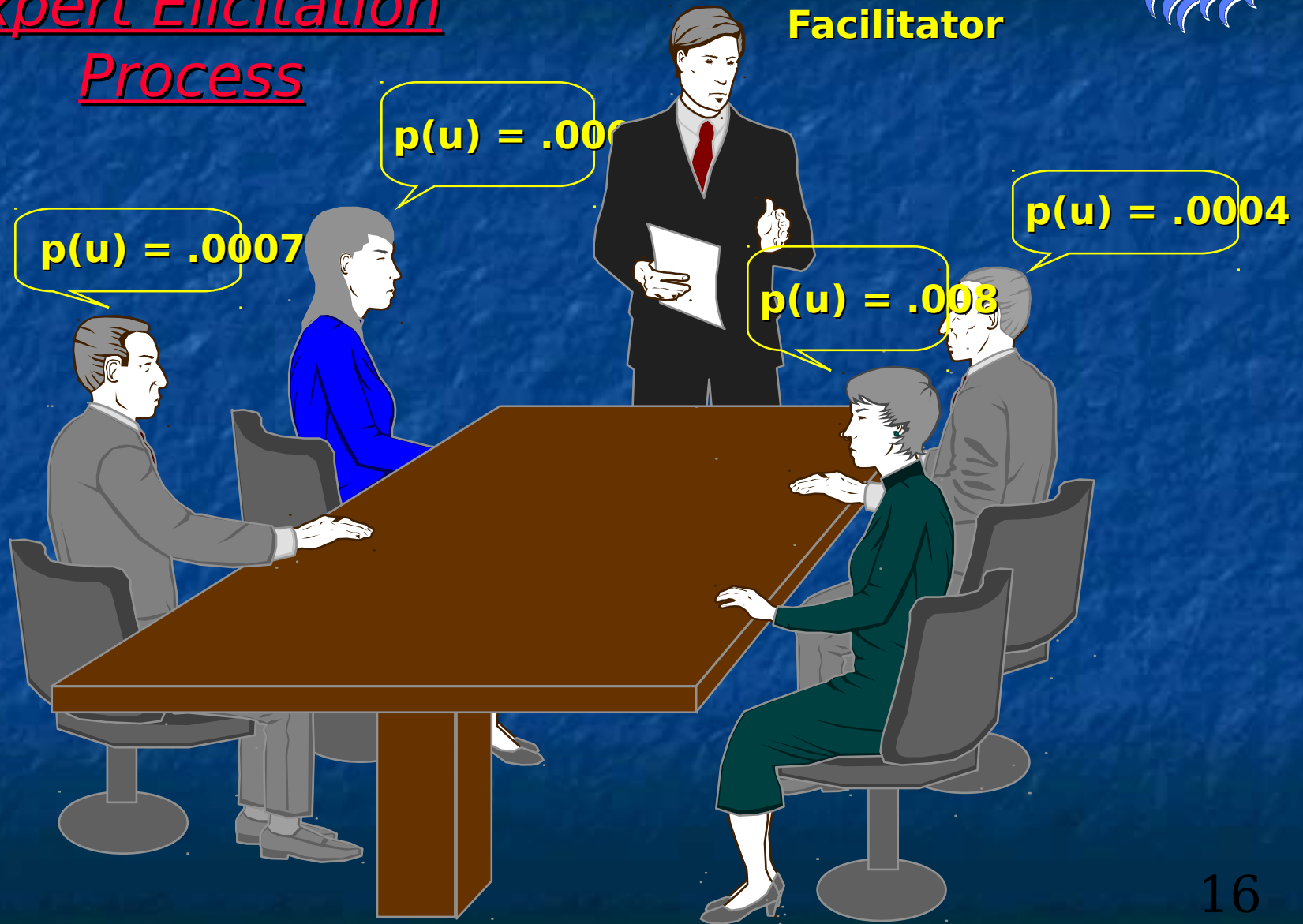
Note: On-going reliability guidance should supercede this guidance over next 2-3 years with an EC on USACE Infrastructure Engineering Reliability Analyses



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Expert Elicitation Process





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Expert Elicitation Process

- Solicitation of “experts” to assist in determining probabilities of unsatisfactory performance or rates of occurrence
- Formal process with a facilitator, panel of experts, observers, and training period to remove bias and dominance
- Should be used to supplement analytical reliability models as part of an overall risk assessment for a project
- Recent project studies using expert elicitation
 - Nashville District (Chickamauga Lock Replacement Study)
 - Pittsburgh District (Ohio River Mainstem Study – Emsworth Lock)
 - Louisville District (Mill Creek Flood Protection Project)
 - Vicksburg District (Lindy C. Boggs Lock Wall Evaluation)



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Historical Frequency Method

Use of known historical information for records at site to estimate the failure rates of various components

Excellent method, but usually USACE projects do not have enough historical failure performance to develop future probabilities

Example: if you had 5 hydraulic pumps in standby mode and each ran for 2000 hours and 3 failed during standby mode, the failure rate would be as follows:

Total standby hours = $5 * 2000 \text{ hours} = 10,000 \text{ hours}$

Failure rate (standby mode) = $3 / 10,000 = 0.0003 \text{ failures/hour}$



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Manufacturer Survivorship Curves

Excellent method that is very similar in nature to historical frequency method

There are enough failures to develop survivorship curves for different components (light bulbs are an excellent example). These are usually provided by the manufacturer for items such as pumps, motors, etc...

Same as historical frequency, USACE components typically do not have enough “failure” events to establish survivorship curves with the exception of some components at hydropower facilities (generators, etc...)



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Probabilistic Methods

Reliability Models Are:

- ✓ defined by random variables and their underlying distributions
- ✓ based upon limit states (analytical equations) similar to those used in design or analysis of a component
- ✓ based upon capacity/demand or safety factor relationships

Two Probabilistic Methods of Developing Reliability Models are Currently in Use within USACE:

- ✓ Reliability Index (β Method)
- ✓ Hazard Function Analysis

Reliability Index (β Method)

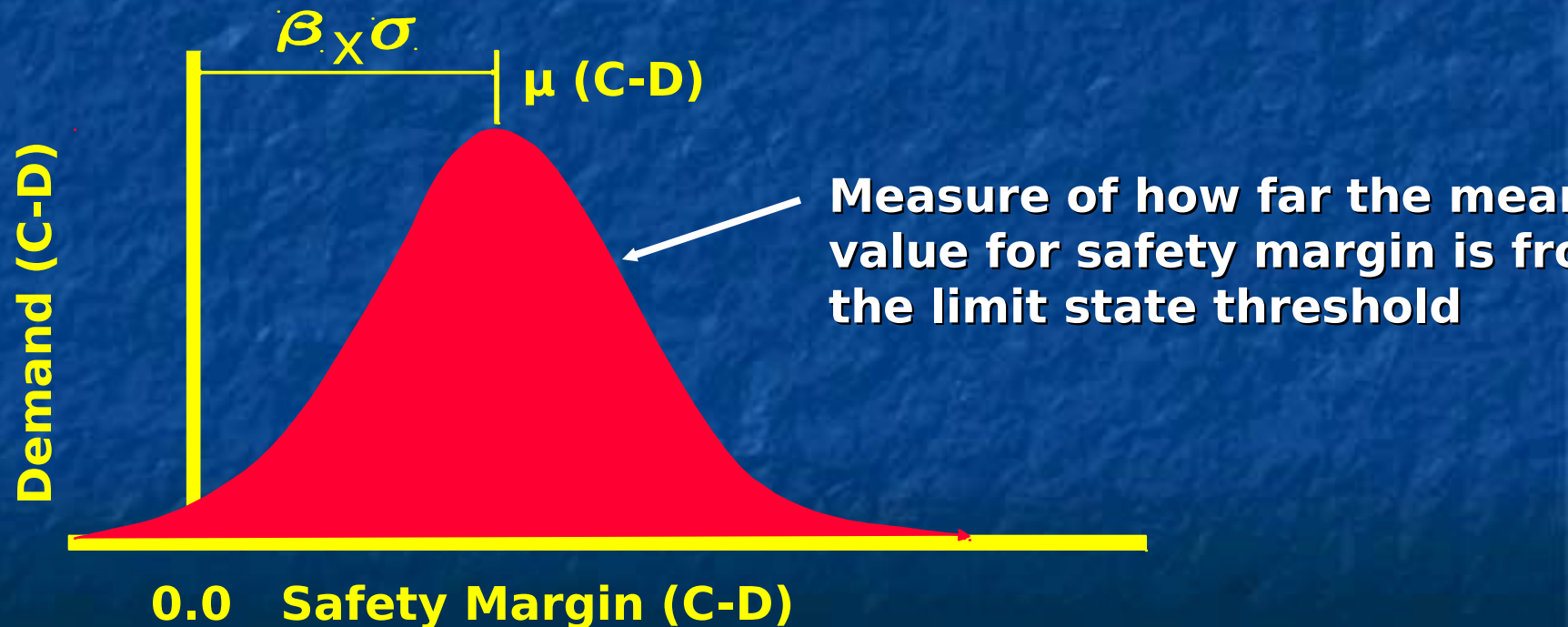
Utilizes Taylor Series Finite Difference

1st order expansion about the mean value

Linear approximation of second moment

Uses a factor of safety approach

Easy to implement in spread sheets



Reliability Index (β Method)

Major Shortcomings Associated with β Method:

- ✓ Instantaneous that represents “snapshot” in time and is not applicable for time dependent structures whose conditions degrade with time
- ✓ Only applicable for a few distribution types and not efficient when there are many random variables and when some are correlated with one another
- ✓ Many times errors made on underlying distributions used to calculate β
- ✓ Originally used when computation power and commercial software was not adequate for simulation model development



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Hazard Function Analysis

Preferred Method of Computing Probabilities of Failure

- ✓ Started with insurance actuaries in England in late 1800's
- ✓ Brought into engineering field with aerospace industry in 1950's
- ✓ Accounts for the knowledge of the past history of component

Computes the Rate of Change at Which the Probability Changes Over a Selected Time Step (Usually Annually)

- ✓ Not a "snapshot" in time, it is truly cumulative
- ✓ Uses Monte Carlo simulation techniques to calculate the true probability of failure (or PUP)
- ✓ Can easily be developed for time dependent and non-time dependent models from deterministic engineering design procedures



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Hazard Function Analysis

Definition:

The hazard function, $h(t)$, is the conditional probability of unsatisfactory performance of a structure or component at time t given that it has survived up to the selected time

$$h(t) = f(t) / R(t)$$

where: $f(t)$ = pdf at time $t + \Delta t$

$R(t)$ = cumulative reliability up to time t

When using Monte Carlo simulation methods it can be simplified to the following formula:

$$h(t) = \# \text{ of failures } (t_i) / \# \text{ of survivors } (t_{i-1})$$



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Summary of Probabilistic Methods

For Components Whose Reliability will not Degrade with Time (Non-Time Dependent Reliability Analysis):

- ✓ Linear limit states with normal or lognormal input distribution types – Reliability Index (β Method) or Monte Carlo simulation methodology is appropriate
- ✓ Non-linear limit states – Monte Carlo simulation methodology
- ✓ Typical USACE examples: gravity structures w/o changing loads

For Components Whose Reliability Degrades with Time (Time Dependent Reliability Analysis):

- ✓ Hazard function analysis using Monte Carlo simulation methodology
- ✓ Typical examples: hydraulic steel structures, deteriorating concrete, anchored walls, mechanical/electrical equipment, etc...



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Basic Features of Reliability Analysis

Basic Parts to a Reliability Analysis

- **Limit State** which is the failure mechanism that is being investigated such as stability of gravity structures or fatigue analysis for steel structures
- **Random Variables** which are input values for the analysis that are allowed to vary according to some distribution. Example might be yield strength of steel, corrosion rate...
- **Constants** are input values to model that hold the same value for each iteration such as unit weight of water, etc.
- **Counter** which tabulates iterations that reach the limit state (or fail) versus those that never fail. Used to track the number of failures and survivors for each time period analyzed.
- **Event Tree** which is developed to show randomness associated with different levels of repair given a failure. This is developed separate of the reliability model and is provided to depict the consequences associated with unsatisfactory performance.



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Required Info for Consequence Analysis

Annual Hazard Rate (Time Dependent Components)

Single PUP (Non-Time Dependent Components)

Consequence Event Tree for Each Component/Scenario

- Only evaluate significant consequences
- Various level of repairs
- Cost to repair & other damages (time out of service, etc...)

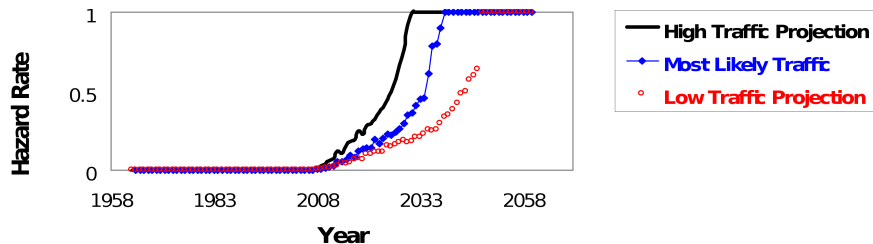
Updated Hazard Rate for Repaired Components

Consequences Associated with Schedule Repair Prior to Failure to Compare vs. Fix-As-Fails Scenario

Engineering Requirements

Reliability Modeling – Outputs and Integration with Economics

Time Dependent Hazard Functions for Varying Traffic Projections



Time dependent probabilities of failure for various alternatives through study period

Component	Annual Hazard Rate	Level of Repair	Closure Time	Repair Cost	Effect on Overall Component Reliability
	Annual Reliability Value (1 - Annual Hazard Rate)				
Horizontally-framed Miter Gate		New Gate 5%	365 days in year 1 90 days in year 2	\$13,150,000 \$3,150,000	Assume R = 1.0 for All Future Years
	Annual Hazard Rate	Major Repair 39%	45 days in year 1 45 days in year 2	\$1,575,000 \$1,575,000	Move Back 5 Years
		Temporary Repair 60%	45 days in year 1	\$3,575,000	Assume R = 1.0 for All Future Years
		Replace 1st Set of Gates	45 days in year 2	\$3,575,000	
		Replace 2nd Set of Gates	30 days in year 3	\$5,050,000	
SCHEDULED REPLACEMENT BEFORE FAILURE INFORMATION Year 1 – 30 Days of Closure @ \$5,050,000 Year 2 – 30 Days of Closure @ \$5,050,000 Future Reliability Will Equal 1.0 Throughout Remainder of Study Period					

Consequence event tree given the limit state is exceeded in the reliability analysis



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Consequence Event Trees



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Consequence Event Trees

Background Information

- ✓ Mechanism That Interfaces Engineering and Consequences
- ✓ Provides Consequences (Repair Cost, Service Disruption Time, Etc.) Associated with Unsatisfactory Performance of Component
- ✓ Critical to Overall Consequence Evaluation for Loss of Life and Economic Damages
- ✓ Information Developed Consistent with Reliability Limit State Modeling
- ✓ Developed for Individual Maintenance Strategies

Consequence Event Tree

Basic Parts

EVENT FREQUENCY -- Determined for each load case being evaluated



RELIABILITY MODEL INPUT -- Given the event occurs, what is the probability of unsatisfactory performance?



RANGE OF FAILURE -- Given limit state being modeled, what are the possible levels of failure given that it occurs?



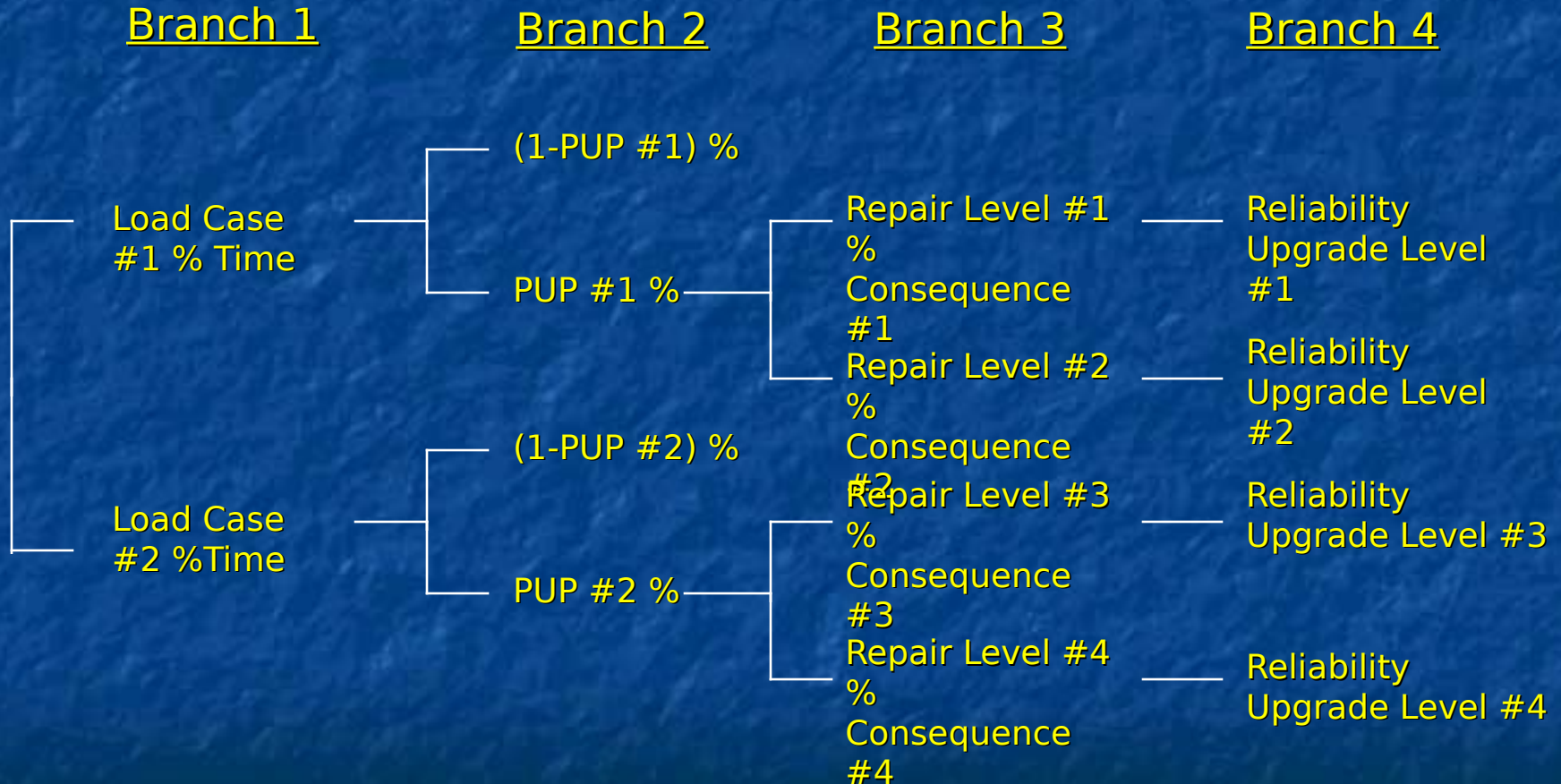
CONSEQUENCES OF FAILURE & REQUIRED REPAIR -- For each level of failure, what are the expected consequences (loss of life, \$\$\$ damages)?



EFFECT ON FUTURE RELIABILITY -- Following the repair, what is the improved reliability for future operations?

Consequence Event Trees

Example Format



Scheduled Repair/Replacement – Cost and Service Disruption Time

Time Dependent Component

Example Event Tree – Culvert Valves

<u>Component</u>	<u>Hazard Rate</u>	<u>Damage/Level of Repair</u>	<u>Repair Cost</u>	<u>Chamber Closure</u>	<u>Future Reliability</u>	
Main Chamber Horiz.-Framed Culvert Valve	Annual Hazard Rate (AHR)	Catastrophic Failure Chamber Closed	1%	\$6,325,000	Closed 15 days in year of failure	R =1.0 for All
		Fabricate and Install 4 New Culvert Valves		Split Over 2 Years	90 days half-speed follow ing year	Future Years
		Temporary Repair to Open Chamber	49%	\$5,000,000	Closed 10 days in year of failure	Move Back
	1- (AHR)	Fabricate and Install 2 New Culvert Valves		Split Over 2 Years	90 days half-speed follow ing year	20 Years
		Major Damage	50%	\$2,100,000	Closed 5 days in year of failure	Move Back
		Major Repairs to Valves				5 Years

Scheduled Replacement of Culvert Valves for Main Chamber

Cost = 4*(400,000) + 90*(35,000) = **\$4,750,000**

No Chamber Closure But **90 Days of Half-Speed Operation**



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Consequence Event Trees

Review of Key Points

- ✓ Links Reliability Analysis to Consequence Evaluation Through Multiple Alternative Scenarios
- ✓ Consequences Consistent with Limit State Being Modeled in Reliability Analysis
- ✓ Significant Limit States/Consequences Effect Evaluation
- ✓ Expert Elicitation is a Good Means to Obtain Event Tree Values when Analytical Methods or Historical Performance is not Available

Planning Requirements for Major Rehab

Multi-Scenario Planning Options – Establishing the WOPC

Key – establish the base condition

Base condition should be calibrated to current field conditions

Deterioration modeling without reliability upgrade repairs

What is future cost to keep project serviceable? What is future reliability?

Advance maintenance repair scenarios

Short-term repair to temporarily upgrade reliability

What is the cost of repair? Service disruption time? Upgraded reliability?

Compare to the baseline plan

Plan with the Highest Net Benefits Determines Optimized WOPC

Developing the With Project Condition

Replacement or long-term repair that provides substantial increase in reliability for the long-term performance of the structure

Repair/replacement must meet Major Rehab cost and time thresholds

Compared to optimized WOPC to determine if it is economically justified

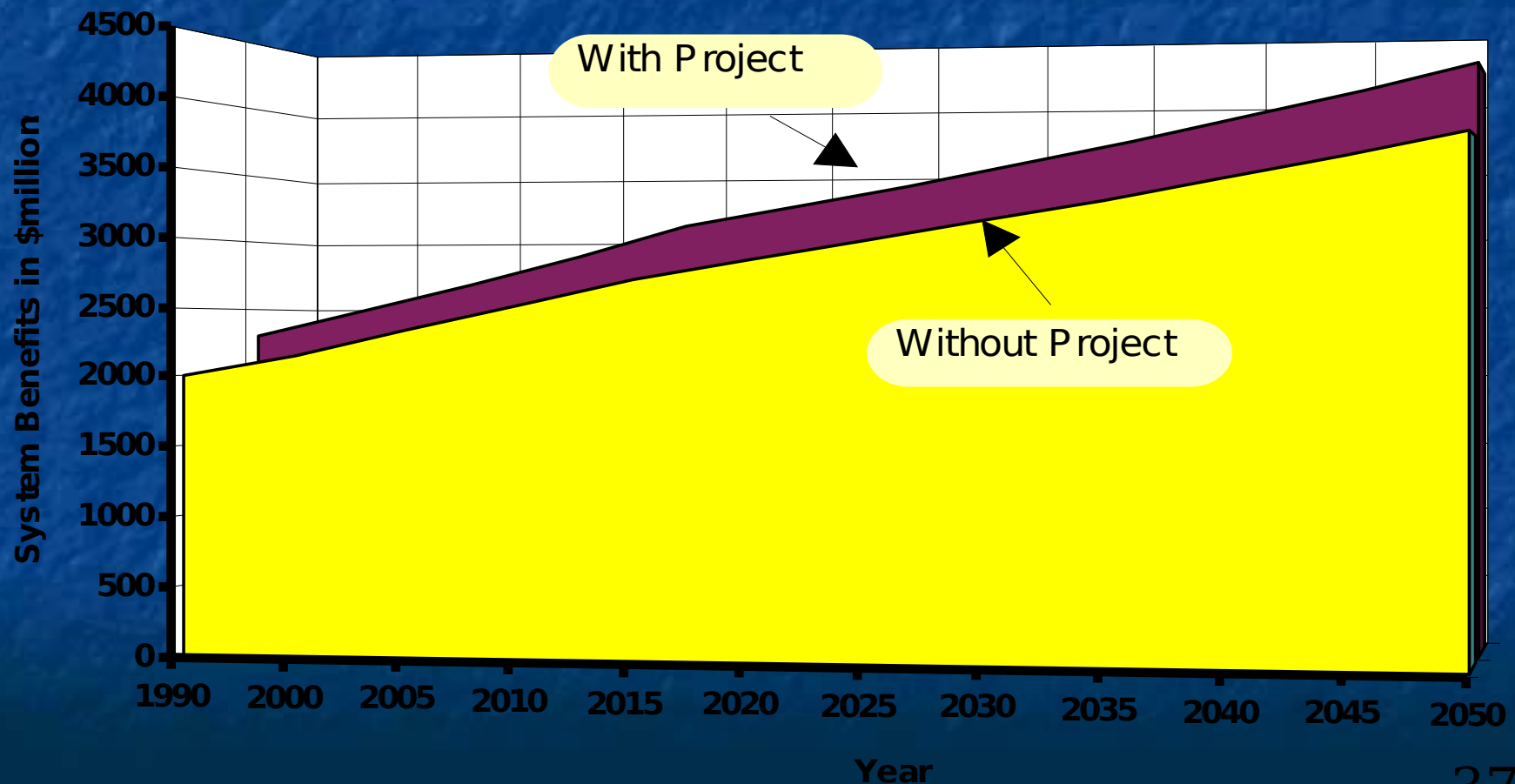


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Economic Analysis

Incremental Benefits w/o Reliability-Based Consequences





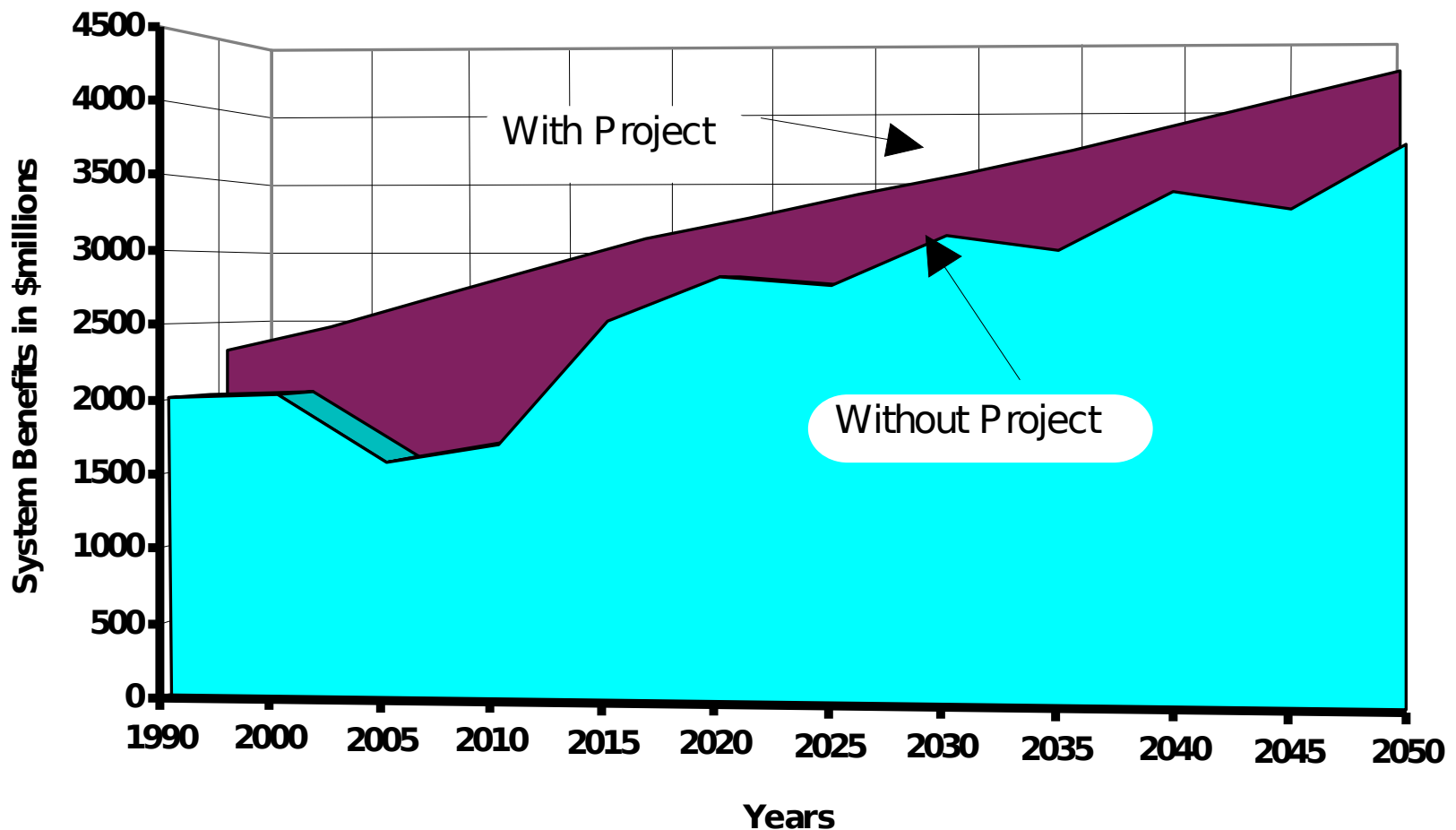
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Economic Analysis

Incremental Benefits with Reliability-Based Consequences





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New Engineering Circular Engineering Reliability Guidance for Existing USACE Civil Works Infrastructure



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New Engineering Reliability Guidance

General Background

Updating engineering reliability guidance sorely needed

No systematic guidance that addresses development of other critical pieces of analysis such as event trees and integration within engineering guidance

Currently, major rehab guidance document (EP 1130-2-500) is the general reliability guidance that has been used, but it is very old and has some outdated information

Major rehab guidance will reference the EC document as the “source to use” for developing engineering reliability analysis

New Engineering Reliability Guidance

Structural Guidance

Currently, there is no structural reliability guidance since previous documents have been rescinded

Previous structural guidance has been rescinded due to more accurate, analytically correct techniques (Monte Carlo simulation) available with commercial software and PC speed

Rescinded structural guidance

- ETL 1110-2-321 "Reliability Assessment of Navigation Structures and Stability of Existing Gravity Structures"
- ETL 1110-2-354 "Reliability of Pile-Founded Navigation Structures"
- ETL 1110-2-532 "Reliability Assessment of Navigation Structures"

New Engineering Reliability Guidance

Existing Geotechnical Guidance

Currently, there are two active geotechnical reliability documents although the main sections of these will be rolled into the new EC document in order to have a single source

Currently active geotechnical guidance

- ETL 1110-2-547 covers basic reliability applications for geotech engineering
- ETL 1110-2-561 covers seepage and slope stability reliability applications for embankment dams

New EC will cover recent developments associated with potential time dependent aspects of seepage & piping reliability

Expired geotechnical guidance

- ETL 1110-2-556 covered reliability assessment of levees

New Engineering Reliability Guidance

Existing Mechanical/Electrical Guidance

Currently, there is one active document related to mechanical and electrical reliability assessments for hydropower projects (ETL 1110-2-550) -- uses survivorship curves

Recently mechanical/electrical guidance (expired June 2006)

- ETL 1110-2-560 covers basic reliability applications for mechanical and electrical aspects of navigation locks and dams
- Overall, the methodology is appropriate, but there are some major changes than need to be made (minor components and failure rate problems)
- Application using these methods had to be used with extreme caution

Current plan for mechanical/electrical guidance

- USACE team of mech/elec engineers, along with reliability experts, will develop applicable failure rates for navigation lock and dam uses
- Only critical components will be considered in the analysis
- Goal is to have updated failure rates and improved method by end FY06
- These improvements will be rolled into the new EC document



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New Engineering Reliability Guidance

General Information

Three Year Plan to Develop Infrastructure Reliability Guidance Engineering Circular (EC)

Initial funds received in FY04 to establish team, set general schedule, outline Guidance will cover all major engineering disciplines (structural, geotechnical, mechanical, electrical, as well as basic economic aspects)

Integration with economics and plan formulation also included

Technical Team Spread throughout USACE

New Guidance Needs to be Incorporated in Major Rehab Evaluation Guidance with Respect to Engineering Requirements

as well as Other Uses (Systems Studies, Evaluation of Existing Deteriorated Structures)

New Engineering Reliability Guidance

March 2005 Progress Review Meeting w/ HQ

FY05 Funds Received in February Limiting Much Progress During First
 $\frac{1}{2}$ of FY

Progress Review Meeting with HQ in March 2005

Refined Outline as Per April 2004 Meeting Used as Guide

Major Portions of Following Main Volume Completed:

- Chapter 1 – Introduction and Background

- Chapter 3 – Engineering Reliability Guidelines

- Chapter 5 – Engineering and Economic Integration

Refocus Document to be More Business Line/Project Oriented

Previous version from FY04 was separated by discipline

New Engineering Reliability Guidance

Major Changes Out of March 2005 Meeting

Personnel at Meeting Approved Idea with Following Taskers from that Meeting

- Create New Technical Appendices on Project/Business Line Basis

- Determine Appropriate POC's to Lead These Appendices

- Revise Main Volume Outline to Pull in General Discussions Regarding Reliability Analysis for Select Disciplines

New Technical Appendices and Technical Leads

- Navigation Appendix (David Schaaf, Louisville)

- Flood Protection Appendix (Robert Patev, New England)

- Hydropower Appendix – (James Nolan, former USACE from HDC)

- Coastal and Port Structures – (Dr. Jeff Melby, ERDC-WES)

Technical Appendices to Contain Practical Examples/Case Studies

Refine Main Volume Sections to Includes General Discipline Guidance

New Engineering Reliability Guidance

Current Status of Document

Outline for Main Volume

1. Introduction & Background (purpose, history, on-going initiatives)
2. Engineering Reliability Guidelines (load cases, criteria analysis)
3. Methodologies for Reliability Analysis (available methods, model set-up)
4. Expert Elicitation Methodology (general overview, when to use)
5. Systems Reliability Applications (component redundancy, parallel, series)
6. Engineering & Economic Integration (event trees, base condition)
7. Risk & Reliability for USACE Studies (major rehab, systems studies)
8. Integration with USACE Dam Safety Program (portfolio risk analysis)
9. Risk and Reliability Issues for Navigation Locks & Dams
10. Risk and Reliability Issues for Flood Control Projects
11. Risk and Reliability Issues for Hydropower Projects
12. Risk and Reliability Issues for Coastal/Port Structures
13. Guidelines for Report Writing
14. References

New Engineering Reliability Guidance

Current Status of Document

Outline for Navigation Lock and Dam Appendix

1. Land Lock Wall Stability Reliability Analysis Example (**ORMSS**)
2. Approach Wall Stability Reliability Analysis Example (**ORMSS**)
3. Simplified Hydraulic Steel Structure Reliability Example (**GLSLS**)
4. HF Miter Gate Reliability Analysis Example (**Markland Major Rehab**)
5. Mass Concrete Deterioration Reliability Example (**Chickamauga**)
6. Concrete Stilling Basin Scour Example (**J.T. Myers Major Rehab**)
7. Miter Gate Machinery Reliability Analysis Example (**ORMSS**)
8. Lock Electrical Systems Reliability Analysis Example (**ORMSS**)

Appendix Examples Have Complete Process of Model Development Including:

Selection of Modeling Features (Random Variables, Constants, Etc...)
Development of Applicable Limit State
Reliability Model Output and Interpretation
Development of Consequence Event Tree
Economic Analysis
Summary of Results

New Engineering Reliability Guidance

Current Status of Document

Outline for Flood Control Appendix

1. Embankments and Levee Examples
 - a. Hodges Village Dam Major Rehab Study
 - b. Wolf Creek Dam Major Rehab Study
2. Outlet Works for Flood Control Projects
 - a. Corrosion/Fatigue of Gates
 - b. Performance of Conduits
3. Concrete Structures for Flood Control Projects
 - a. Erosion of Spillways
 - b. Alkali Aggregate Reaction
4. M/E Equipment for Flood Control Projects
 - a. Reliability Block Diagrams (Wolf Creek)
 - b. Fault Tree Analysis (Wolf Creek)

New Engineering Reliability Guidance

Current Status

During FY06, Main Personnel Developing Document
Redirected to Katrina Work

Others working on guidance heavily involved with Dam Safety SPRA

Originally Scheduled for Draft EC by 30 Sep 06

May Have Slight Extension into FY07 to Wrap Up Draft
Document

Handing Off to A/E or Others Not the Best Option for
Completing a Comprehensive EC that Meets Intended
Need



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Reasons to Establish DX for Risk & Reliability

Requested by Jerry Barnes at 2005 USACE Infrastructure Conference in St. Louis

Risk and Reliability Becoming Cornerstone Analysis Tool for Developing Systematic Investment Plans

- Dam Safety Portfolio Risk Assessment (PRA)

- Navigation River Systems Studies (ORMSS, GLSLS)

- Major Rehabilitation Program (Increasing with Aging Infrastructure)

- Asset Management and Metrics for O/M Budgeting

Problems Across USACE with Appropriate R&R Applications

- No Experienced Group to Lead and Review Risk-Based Studies

- Districts Applying Methodology Inappropriately and Inconsistently

- DX Serve as USACE Review Team for Engineering R & R Applications

Need Engineering Group to Coordinate On-Going R&D Efforts with IWR and ERDC

Integrated with Planning CX for Inland Navigation in Huntington District

Training and Building USACE Expertise in Risk and Reliability

Risk and Reliability Work for Others

- Panama Canal Authority (Full Scale Risk Assessment for ACP)

- Canadian Government (Transport Canada Requests USACE Expertise)



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Responsibilities of R&R DX

Dam Safety Program

- ✓ PRA Tool Methodology & Process Development
- ✓ Train Field Engineers/Economists on Use of PRA Tool
- ✓ Future Center for Review of PRA Analysis and DSA Studies
- ✓ Future R&D Efforts for Modification of PRA Process

Major Rehabilitation Program

- ✓ Train Field Engineers/Economists on Analysis Techniques/Requirements
- ✓ Center of Review for Future Major Rehab Studies

General HQUSACE Directed Efforts

- ✓ Engineering Risk and Reliability Guidance
- ✓ Integrating R & R into USACE Asset Management Program
- ✓ Lead R & D for Model Development through IWR and ERDC

International Work for Others

- ✓ Great Lakes and St. Lawrence Seaway Study
- ✓ Panama Canal Authority Infrastructure Risk and Reliability Study



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Thank You

Questions???

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